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Infestation and spatial dependence of weed seedling and mature weed populations in corn

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Knowing the distribution of weed seedlings in farmer-managed fields could help researchers develop reliable distribution maps for site-specific weed management. With a knowledge of the spatial arrangement of a weed population, cost effective sampling programs and management strategies can be designed, so inputs can be selected and applied to specific field areas where management is warranted. In 1997 and 1998, weeds were sampled at 612 to 682 sites in two center pivot irrigated corn fields (71 and 53 ha) in eastern Colorado. Weeds were enumerated when corn reached the two-leaf, four-leaf, and physiological maturity stages in a 76.2- by 76.2-m grid, a random-directed grid where sites were established at intervals of 76.2 m, and a star configuration based on a 7.62- by 7.62-m grid within three 23,225 m^2 areas. Directional correlograms were calculated for 0, 30, 60, 90, 120, and 150° from the crop row. Fifteen weed species were observed across fields. Spatial dependence occurred in 7 of the 93 samples (a collection of sampling units for a particular weed species that was detected within a field at a particular sampling time and year) for populations of field sandbur, pigweed species, nightshade species, and common lambsquarters. Correlogram analysis indicated that 18 to 72% of the variation in sample density was a result of spatial dependence over a geographic distance not exceeding 5 to 363 m among the examined data. Because of the lack of spatial correlation for weed seedling distributions in these eastern Colorado corn fields, interpolated density maps should be based on grid sizes (separation distances) less than 7.62 m for weed seedling infestations.

Nomenclature: Common lambsquarters, *Chenopodium album* L. CHEAL; field sandbur, *Cenchrus longispinus* (Hack.) Fern CCHPA; nightshade spp., *Solanum* spp.; pigweed spp., *Amaranthus* spp.; corn, *Zea mays* L.

Key words: Geostatistics, map, sampling, spatial correlogram, spatial structure, weed distribution.

Weed management inputs may be more efficiently applied if producers had accurate representations of the spatial distribution of weeds in fields. Management inputs could be focused on field sections only where necessary, thus reducing management costs and possibly increasing profits (Johnson et al. 1995). However, varying the inputs within a field requires reliable distribution and density maps of weed populations. Weed distribution maps could be used to make decisions on where to treat, as well as on the type and intensity of the input (management map). The accuracy of a weed distribution map and the usefulness of the recommendation for the inputs will vary with the accuracy of the estimating density and spatial distribution of each weed population (Audsley and Beaulah 1996).

The mean density and spatial distribution of a pest population can be estimated by sampling. A sampling program to estimate a pest infestation is defined as a procedure that specifies how to collect information for an attribute at a particular time and sampling unit, which is placed at multiple locations within a field (Pedigo 1994). The accuracy of the sampling program must be balanced against the cost of gathering information if growers are to implement a particular sampling program (Buntin 1994). Investigating the characteristic distribution of a weed population could lead to the development of reliable sampling programs for map generation.

To describe the spatial distribution of a weed population, frequency distribution methods, such as Iwao's patchiness regression (Iwao 1968), Taylor's power law (Taylor 1961), and negative binomial (Anscombe 1949), have been used. These methods only infer the spatial relationships from the variance in density, whereas the relative location of the sample units is not considered. An alternative approach for the characterization of spatially variable ecological data, such as weed populations, is geostatistical analysis. Geostatistical techniques are a way to quantify and model the spatial dependence and map a phenomenon (Isaaks and Srivastava 1989). In particular, correlation, covariance, and semivariance functions have been employed to describe spatial distribution or continuity of pest densities (Cardina et al. 1996; Donald 1994; Heisel et al. 1996; Johnson et al. 1996; Midgarden et al. 1993; Mortensen et al. 1993; Mulugeta and Boerboom 1999; Turechek and Madden 1999; Weisz et al. 1995). These three functions use the value and location of each sampling unit to summarize the spatial dependence among points at various distances and directions across a field for a sample. When a pest such as a weed population exhibits spatial dependence, the value at one location and the values at other locations are correlated as a function of incremental distance (Rossi et al. 1992; Weisz et al. 1995).

Knowing more about the spatial distribution of weed

populations will assist in determining whether interpolated weed maps can be created for site-specific management. A sampling program developed to help create an accurate distribution map of the population would need to include observations closer together than the distance of spatial dependence (Weisz et al. 1995). However, if a scout wanted to estimate a mean density, a sampling program would need to include a number of observation pairs greater than the distance of spatial dependence to ensure that sample data are not autocorrelated (Weisz et al. 1995).

To date, few studies have investigated the spatial dependence of weed seedling populations within entire fields. A study by Johnson et al. (1996) evaluated the spatial dependence of velvetleaf (*Abutilon theophrasti* L.) and common sunflower (*Helianthus annuus* L.) across a 2-yr period in a 189- by 224-m field section in Nebraska. Spatial dependence for velvetleaf seedlings was observed for up to 30 m when the field section was planted with either soybean [*Glycine max* (L.) Merr.] or corn. However, the range for common sunflower did not exceed 30 m when the field was planted with soybean but decreased to 8 m the following year when planted with corn. Another study, Cardina et al. (1996), evaluated the spatial dependence of common lambsquarters and annual grass populations in two 25- by 90-m field sections that were planted with soybean for 4 yr in Ohio. It was determined that common lambsquarters populations were spatially dependent to 63.4 m, whereas annual grass populations were spatially dependent to 5.3 m when fields were moldboard plowed (Cardina et al. 1996). Both studies indicated that spatial dependence might be influenced by interactions of weed biology, local microenvironmental conditions, and agricultural practices (Cardina et al. 1996; Johnson et al. 1996).

Producers are requesting more detailed information on where and at what density weeds occur in fields, in order to make informed management decisions on what input to apply by location. The lack of field-specific data on the infestation and spatial distribution of weeds, as well as the cost of sampling, are obstacles to the development of optimal sampling programs for growers to make site-specific management decisions. By knowing more about the weed infestation and distribution within fields, the cost and benefits of applying management inputs to selected field areas using management maps can be adequately assessed. The objective of this study was to investigate the spatial dependence of weed seedling and mature weed populations in two corn fields for a 2-yr period in eastern Colorado to facilitate the future design of optimal sampling programs for creating reliable weed distribution maps that could be used for site-specific management.

Materials and Methods

Field Sites

Two grower-managed center-pivot irrigated corn fields (71 and 53 ha), located in Morgan County near Wiggins, CO, were sampled in 1997 and 1998. Soils on both pivots included a Valentine sand (sandy, mixed nonacid, mesic Typic Ustipsamment), a Bijou loamy sand (coarse loamy, mixed, mesic Mollic Haplargid), and a Truckton loamy sand (coarse loamy, mixed, mesic Udic Argiustoll). The crop rotation for Field 1 was corn in 1993, corn in the northwest half and northeast quarter (crop rows were orientated in a northeast to southwest direction) and onions (*Allium cepa* L.) in the southeast quarter in 1994, corn in 1995, sugar beet (*Beta vulgaris* L.) in 1996, and corn in 1997 and 1998. Crop rotation in Field 2 was sugar beet (northwest half) and pinto bean (*Phaseolus vulgaris*) (southeast half) in 1993, corn in 1994 and 1995, sugar beet in 1996, and corn in 1997 and 1998. Herbicides were selected and applied by each producer (Table 1).

Sampling Grids

Weed populations were sampled on three grid systems established within each field (Figure 1). Weed sampling sites (locations where sampling units were placed) were established within crop rows on a 76.2- by 76.2-m grid. Additional sampling sites (random-directed grid) were established within the direction of the crop row for each interval of 76.2 m. Each random-directed sampling site was established at randomly selected increments of 5.08 m within each 76.2-m interval. In addition, three 23,225 m^2 square areas (152.4 by 152.4 m) were randomly chosen in each field, wherein 150 sites were established in a star configuration based on a 7.62- by 7.62-m grid (star grids A, B, and C). The random-directed and star grids were established to investigate spatial dependence at distances less than 76.2 m. Across all grids, a total of 682 sites were sampled in Field 1 and 621 sites were sampled in Field 2 in 1997, whereas in 1998, 679 sites were sampled in Field 1 and 612 sites were sampled in Field 2 (Table 2). Directly after corn planting each year, each sampling site within a field was established and referenced with an OmniSTAR 7000[1] differential global positioning system and marked with a flag for locating throughout the growing season.

Weed Sampling

Weed seedlings or mature weeds were counted by species or species complex at each sampling site within a 1.52- by 0.15-m sampling unit in 1997 and 1998. The sampling unit was used previously to estimate weed densities for the determination of management decisions with a computer decision aid, WEEDCAM (Schweizer et al. 1994). Weed densities were determined when corn was at the two-leaf stage (before postemergence herbicide treatment), four-leaf stage (after postemergence herbicide treatment), and physiological maturity (before harvest) (Table 3). In addition, three plants of each species or species complex were randomly selected at physiological maturity to determine the presence of flowers.

Geostatistical Analysis

The spatial dependence of each weed species per sample (a collection of sampling units for a particular weed species within a field at a particular sampling time and year) was described by examining the spatial correlograms. A spatial correlogram is a plot of correlation coefficient values for sampling units (weed density) that are separated by various geographic distances (lag) and in a particular direction (Liebhold et al. 1993). Correlogram functions [$\rho(h)$] may be a better tool to quantify spatial dependence than variograms [$\gamma(h)$] because correlogram functions filter out local

TABLE 1. Herbicide treatments in two eastern Colorado irrigated fields of corn (*Zea mays*) during 1997 and 1998.

	Herbicide treatment							
	Field 1				Field 2			
	1997		1998		1997		1998	
Application time[a]	Herbicide	Rate	Herbicide	Rate	Herbicide	Rate	Herbicide	Rate
		kg ai ha^{-1}		kg ai ha^{-1}		kg ai ha^{-1}		kg ai ha^{-1}
PRE	Glyphosate	1.12	Metolachlor +	2.18	Glyphosate	1.12	—[b]	—
	Atrazine	2.02	cyanazine	2.24	Metolachlor	1.94		
POST	Nicosulfuron[c] +	0.01	Nicosulfuron +	0.01	Pyridate +	0.91	Nicosulfuron +	0.01
	rimsulfuron +	0.01	rimsulfuron +	0.01	atrazine	2.02	rimsulfuron +	0.01
	atrazine	0.81	atrazine	0.81			atrazine	0.81
			Diglycolamine	0.14			Pyridate	0.49

[a] PRE, preemergence; POST, postemergence.
[b] Dashes (—) indicate that no herbicides were applied.
[c] Nicosulfuron, rimsulfuron, and atrazine were formulated as a premix.

FIGURE 1. Arrangement of established sample sites in three grid types in Field 1. Sampling site establishment in Field 2 was similar to that in Field 1.

mean and variance trend effects that may occur over the sampling space (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). A correlogram value can only vary from +1 to −1 depending upon whether the correlation between the sampling units is positive or negative (Rossi et al. 1992). Correlograms, unlike variograms, tend to have large coefficient values (h) at short dis-

TABLE 2. Number of sampling units established by field, grid, and year in two eastern Colorado irrigated fields of corn (*Zea mays*) during 1997 and 1998.

	Sampling units			
	Field 1		Field 2	
Grid type[a]	1997	1998	1997	1998
	no.			
Regular	122	121	91	86
Random-directed	110	108	80	76
Star A	150	150	150	150
Star B	150	150	150	150
Star C	150	150	150	150
Total	682	679	621	612

[a] Grid types are shown in Figure 1.

TABLE 3. Sampling dates for weed seedlings or mature weeds in two eastern Colorado irrigated fields of corn (*Zea mays*) during 1997 and 1998.

Sampling time	Corn growth stage	Sampling date			
		Field 1		Field 2	
		1997	1998	1997	1998
1: Before postemergence herbicide treatment	V2	3 June	27 May	3 June	28 May
2: After postemergence herbicide treatment	V4	28 June	18 June	20 June	19 June
3: Before corn harvest	R6	29 September	16 September	23 September	19 September

tances and small values at longer distances (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). Spatial correlograms were calculated using Equation 1,

$$\rho(h) = \frac{1}{N(h)} \sum_{(ij)|h_{ij}=h} (v_i v_j - m_{(-h)} m_{(+h)})/\sigma_{(-h)}\sigma_{(+h)} \quad [1]$$

where the tail mean $m_{(-h)}$ is given by Equation 2,

$$m_{(-h)} = \frac{1}{N(h)} \sum_{i|h_{ij}=h} v_i \quad [2]$$

the head mean $m_{(+h)}$ is given by Equation 3,

$$m_{(+h)} = \frac{1}{N(h)} \sum_{j|h_{ij}=h} v_j \quad [3]$$

where $N(h)$ is the number of pairs of points separated by the distance h, v_i is the weed density at location i, v_j is the density at location j which is separated from location i by the distance h, $\sigma_{(-h)}$ is the lag standard deviation of v_i, and $\sigma_{(+h)}$ is the lag standard deviation of v_j (Isaaks and Srivastava 1989). The $m_{(-h)}$ is the mean of the weed density values at sample sites at a distance $-h$ away from some other sample sites and $m_{(+h)}$ is the mean weed density at all sample sites at a distance $+h$ away from some other sample site. For ease of interpretation, we subtracted the correlation function from one (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995), as shown in Equation 4:

$$\gamma(h) = 1.0 - \frac{1}{N(h)} \sum_{(i,j)|h_{ij}=h} (v_i v_j - m_{(-h)} m_{(+h)})/\sigma_{(-h)}\sigma_{(+h)} \quad [4]$$

After transforming each correlation to variogram form, coefficient values tend to be small at short distances between sample sites h and large at longer distances h (Isaaks and Srivastava 1989; Liehold et al. 1993; Rossi et al. 1992). Correlograms were used to describe the correlation between weed density at various locations and the distance between these locations. These are presented in variogram form and are represented as $\rho(h)$, with the transformed correlation values plotted against distances between sample sites (h).

Important features of the correlogram in variogram form include the nugget, sill, and range (Isaaks and Srivastava 1989). A nugget (correlation value at the y-intercept) that is nonzero represents microscale variation below the sampling scale and experimental or measurement error (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The value at which the plotted points or individual coefficient values plateau is the sill (Rossi et al. 1992). When the correlation coefficient values of the transformed correlogram are plotted as a function of distance, the sill will be equal to one (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The distance at which the correlation values level off to an asymptote or the sill is known as the range, which defines the maximum distance up to which the sampling units (weed densities) remain correlated spatially (spatial dependence) (Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). The difference between the sill and the nugget represents the proportion of the total variation that is explained by the spatial dependence with the implemented sampling program (Rossi et al. 1992).

Spatial dependence for each sample was analyzed at a total of six horizontal directions of 0, 30, 60, 90, 120, and 150° from the crop rows. In addition, the weed density data from each sample from the northwest and the southeast half of each field were examined separately for spatial dependence because previous crop rotations may have influenced the spatial distribution of these weeds. The angles were measured from the crop row for each field (Figure 1). Lag increment was set at 9 m, which was the average separation distance among established sampling units. The minimum number of paired sampling units at each lag was set to 30 to ensure an accurate estimate of variance (Liebhold et al. 1993; Rossi et al. 1992). In addition, each sample correlogram in variogram form was weighted by the number of pairs per lag. All spatial analyses were conducted using SAGE95[2] geostatistical software. SAGE95 software is able to calculate multiple directional sample correlograms in variogram form and simultaneously model the experimental correlogram. All correlogram coefficients for the six investigated directions within a sample were simultaneously considered to estimate one nugget (spatial variation below the minimum distance between sampling sites, or experimental or measurement error for a sample) and a range for each direction. Each directional correlogram in variogram form was jointly fit with a spherical model for each direction, and best fit was determined by least squares.

Results and Discussion

Infestation

Fifteen weed species or species complexes were detected in Field 1 (Table 4) and Field 2 (Table 5). More species were detected at the first sampling time than the other two sampling times for both fields. Species of pigweed, nightshade, common puncturevine (*Tribulus terrestris* L.), foxtail (*Setaria* spp.), and field sandbur in Field 1, as well as field sandbur in Field 2, were detected at each sampling time. The winter annual species, prickly lettuce (*Lactuca serriola*

TABLE 4. Density of weed seedling or mature weeds by species or species complex before and after postemergence herbicide treatment in corn (*Zea mays*), and before corn harvest in Field 1 during 1997 and 1998.

Sampling time[a]	Species[b]	Weed density						Weed-free sampling units	
		Mean (Standard deviation)		Median		Maximum			
		1997	1998	1997	1998	1997	1998	1997	1998
		no. sampling unit^{-1}						%	
1	*Solanum* spp.	0.5 (3.8)	0.2 (1.0)	0	0	87	11	90	92
	Amaranthus spp.	1.9 (8.7)	1.0 (0.4)	0	0	99	42	71	80
	CHEAL	< 0.1 (0.2)	< 0.1 (0.1)	0	0	6	1	99	99
	HELAN	< 0.1 (0.3)	—[c]	0	—	7	—	99	100
	TRBTE	0.1 (0.7)	< 0.1 (1.0)	0	0	15	15	98	96
	KCHSC	0.1 (1.2)	—	0	—	32	—	99	100
	SASKR	< 0.1 (<0.1)	< 0.1 (0.2)	0	0	1	2	99	97
	CIRAR	< 0.1 (0.1)	—	0	—	2	—	99	100
	Setaria spp.	< 0.1 (0.6)	< 0.1 (0.1)	0	0	14	2	97	99
	CCHPA	0.3 (3.0)	0.2 (1.5)	0	0	67	33	91	96
	ECHCG	< 0.1 (0.3)	< 0.1 (<0.1)	0	0	5	1	97	99
	XANST	—	< 0.1 (0.1)	—	0	—	3	100	99
2	*Solanum* spp.	0.1 (0.9)	< 0.1 (0.1)	0	0	18	2	96	99
	Amaranthus spp.	0.8 (2.5)	0.1 (0.4)	0	0	27	5	73	93
	ABUTH	< 0.1 (< 0.1)	< 0.1 (0.1)	0	0	1	1	96	99
	TRBTE	0.2 (2.0)	< 0.1 (0.2)	0	0	32	4	95	98
	KCHSC	< 0.1 (0.1)	—	0	—	1	—	96	100
	SASKR	—	< 0.1 (0.2)	—	0	—	2	100	98
	XANST	—	< 0.1 (0.1)	—	0	—	2	100	99
	Setaria spp.	0.1 (0.8)	< 0.1 (0.6)	0	0	17	16	95	99
	CCHPA	0.1 (1.5)	0.1 (0.8)	0	0	34	21	94	98
3	*Solanum* spp.	0.4 (1.3)	0.1 (0.5)	0	0	15	6	76	94
	Amaranthus spp.	2.9 (4.3)	0.6 (1.7)	1	0	42	36	32	64
	TRBTE	< 0.1 (0.1)	< 0.1 (0.1)	0	0	1	3	96	99
	LACSE	< 0.1 (0.2)	< 0.1 (0.2)	0	0	2	1	94	97
	CAPBP	0.1 (0.3)	< 0.1 (0.2)	0	0	3	3	90	98
	CHEAL	< 0.1 (0.6)	< 0.1 (0.1)	0	0	14	1	96	99
	Setaria spp.	0.2 (1.3)	< 0.1 (0.1)	0	0	22	2	90	99
	CCHPA	0.1 (1.7)	< 0.1 (0.1)	0	0	16	2	94	99

[a] Sampling time—1: before postemergence herbicide treatment at V2 corn; 2: after postemergence herbicide treatment at V4 corn; 3: before corn harvest at R6 corn.

[b] Shepherd's-purse, *Capsella bursa-pastoris* L. Medic. CAPBP; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; common sunflower, *Helianthus annus* L. HELAN; kochia, *Kochia scoparia* (L.) Schard KCHSC; prickly lettuce, *Lactuca serriola* L. LACSE; foxtail spp., *Setaria* spp.; Russian thistle, *Salsola iberica* Sennen. & Pau SASKR; puncturevine, *Tribulus terrestris* L. TRBTE; common cocklebur, *Xanthium strumarium* L. XANST.

[c] Dashes (—) indicate that the species or species complex was not detected.

L.) and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medic], were only detected at the last sampling time because they survived control by germinating late in the growing season.

Weed densities among sampling times may be influenced by herbicide application, type and timing of management inputs, environmental conditions, and the biology of each weed species (Cardina et al. 1997). In particular, pigweed species continued to germinate and emerge throughout the season in Field 1 during 1997 (Table 4 and Figure 2). For the third sample time in 1997, only 32% of the sampling units were free of pigweed species (Table 4). Of the sampling units where a pigweed plant was present, 56% had one or more plants that were flowering (Figure 2). However, most of the flower production was not in the southeast area of the field where pigweed seedlings first emerged early in the season (Figure 2A) but in the northwest area where pigweed seedlings emerged after postemergence herbicide application (Figure 2D). Although most of the flower production occurred in the northwest area of the field (Figure 2D), most of the pigweed emergence in 1998 occurred in the southeast portion (Figure 2E), similar to 1997 (Figure 2A). Knowing that the pigweed population germinated in similar locations in 1997 (Figure 2A) and 1998 (Figure 2E) may indicate that sampling to map the pigweed infestation may not be necessary every year. Similarly, a study by Gerhards et al. (1997) in a corn–soybean rotation and another study by Walter (1996) in a spring wheat (*Triticum aestivum* L.)–winter wheat–sugar beet rotation, both determined that selected broadleaf species were stable, thus suggesting that weed maps could be used to predict future seedling distributions, thereby minimizing sampling efforts.

Weed-free sampling units ranged from 1 to 100% among fields and years (Tables 4 and 5). Fifty-four of 58 samples in Field 1 (Table 4) and 61 of 65 samples in Field 2 (Table 5) had 90% or more weed-free sampling units. The large percentage of weed-free areas in both fields was similar to that observed by Johnson et al. (1995), where weed populations were studied in small field portions in Nebraska. They documented that management inputs could be reduced by 30 to 70% by applying inputs only to weedy areas. However, to assess the costs and benefits of implementing site-specific herbicide applications it will be important to

TABLE 5. Density of weed seedling or mature weeds by species or species complex before and after postemergence herbicide treatment in corn (*Zea mays*), and before corn harvest in Field 2 during 1997 and 1998.

Sampling time[a]	Species[b]	Weed density						Weed-free sampling units	
		Mean (Standard deviation)		Median		Maximum			
		1997	1998	1997	1998	1997	1998	1997	1998
		no. sampling unit^{-1}						%	
1	*Solanum* spp.	5.1 (18.0)	9.7 (18.3)	0	4	292	138	59	17
	Amaranthus spp.	3.5 (7.5)	37.0 (23.3)	1	32.5	67	135	42	1
	CHEAL	0.3 (3.5)	2.0 (8.3)	0	0	68	104	94	75
	HELAN	< 0.1 (0.1)	0.1 (0.6)	0	0	2	15	99	97
	TRBTE	< 0.1 (0.6)	< 0.1 (0.1)	0	0	15	1	99	98
	KCHSC	< 0.1 (0.1)	< 0.1 (0.1)	0	0	2	1	99	98
	SASKR	0.1 (0.4)	0.3 (0.7)	0	0	3	4	91	82
	Setaria spp.	—[c]	0.1 (0.5)	—	0	—	8	100	94
	CCHPA	< 0.1 (0.6)	0.1 (0.5)	0	0	12	6	97	90
	ECHCG	—	0.1 (3.3)	—	0	—	79	100	98
	XANST	< 0.1 (0.1)	< 0.1 (0.1)	0	0	1	1	99	99
2	*Solanum* spp.	< 0.1 (< 0.1)	—	0	—	1	—	99	100
	Amaranthus spp.	< 0.1 (0.2)	—	0	—	3	—	99	100
	TRBTE	< 0.1 (0.1)	—	0	—	2	—	99	100
	CHEAL	< 0.1 (0.1)	—	0	—	3	—	99	100
	HELAN	< 0.1 (0.1)	—	0	—	1	—	99	100
	Setaria spp.	< 0.1 (< 0.1)	< 0.1 (0.1)	0	0	1	1	99	99
	CCHPA	< 0.1 (0.4)	< 0.1 (0.1)	0	0	6	1	98	99
3	*Solanum* spp.	< 0.1 (0.1)	0.1 (0.2)	0	0	1	2	98	96
	Amaranthus spp.	0.2 (0.8)	0.2 (0.6)	0	0	8	5	86	87
	LACSE	< 0.1 (0.1)	< 0.1 (< 0.1)	0	0	1	1	98	98
	CAPBP	0.1 (0.3)	< 0.1 (0.1)	0	0	3	2	92	97
	CHEAL	—	< 0.1 (0.1)	—	0	—	3	100	98
	Setaria spp.	< 0.1 (< 0.1)	< 0.1 (< 0.1)	0	0	1	1	99	98
	CCHPA	< 0.1 (0.2)	< 0.1 (0.1)	0	0	3	1	99	99

[a] Sampling time—1: before postemergence herbicide treatment at V2 corn; 2: after postemergence herbicide treatment at V4 corn; 3: before corn harvest at R6 corn.

[b] Shepherd's-purse, *Capsella bursa-pastoris* L. Medic. CAPBP; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; common sunflower, *Helianthus annus* L. HELAN; kochia, *Kochia scoparia* (L.) Schard KCHSC; prickly lettuce, *Lactuca serriola* L. LACSE; foxtail spp., *Setaria* spp. Russian thistle, *Salsola iberica* Sennen. & Pau SASKR; puncturevine, *Tribulus terrestris* L. TRBTE; common cocklebur, *Xanthium strumarium* L. XANST.

[c] Dashes (—) indicate that species was not detected.

assess not only the amount of weed-free area but also its spatial arrangement (Audsley 1993). Samples where 90% or fewer sampling units were weed-free occurred for pigweed species at the first, second, and third sampling time in Field 1 during 1997, nightshade species at the third sampling time in Field 1 during 1998, and for pigweed species and nightshade species at the first sampling time in Field 2 during 1997 and 1998. For these fields, a uniform application may be better than site-specific management because most of the sampling units were infested with one or more pigweed plants.

Spatial Dependence

Spatial dependence (weed densities at one location were correlated as a function of incremental distance and direction to weed densities at other locations) was detected for 7 of 93 samples for pigweeds, nightshades, field sandbur, and common lambsquarters (Table 6). These species were the most abundant in both fields (Tables 4 and 5). Spatial dependence was only detected for samples before a postemergence herbicide application, except for the pigweed sample in Field 1 at the second sampling time during 1997 (Table 6). On the basis of these samples, spatial dependence of weed densities ranged within 5 to 363 m, depending on sample and direction. However, 86% of the ranges for the six directions were less than 100 m, and the average range for the six directions was 57 m. Detected ranges in this study were similar to studies that examined the spatial dependence of common lambsquarters (Cardina et al. 1996) as well as common sunflower and velvetleaf seedlings (Johnson et al. 1996). In these studies, spatial dependence ranged from 4.5 to 80 m (Cardina et al. 1996; Johnson et al. 1996). In particular, Cardina et al. (1996) determined that common lambsquarters was spatially correlated to a distance of 4.5 to 63.4 m, depending on whether soybean fields were subjected to no-till or moldboard plowing over 4 yr.

Even though spatial dependence was detected for seven samples, the variability in weed density between sampling units at very small distances (less than 9 m) was often high (Table 6). Nugget values occurred from 0.28 to 0.82, indicating that 72 to 18% of the variation in sample density was explained by spatial dependence over a geographic distance that ranged within 5 to 363 m, depending on direction. In addition, because each correlogram by direction for a particular sample was simultaneously fit with a spherical model, most of the information for estimating the nugget and range has come from directions where sampling sites were separated at closer distances. Specifically, spatial dependence was detected for pigweed samples in Field 1 in 1997

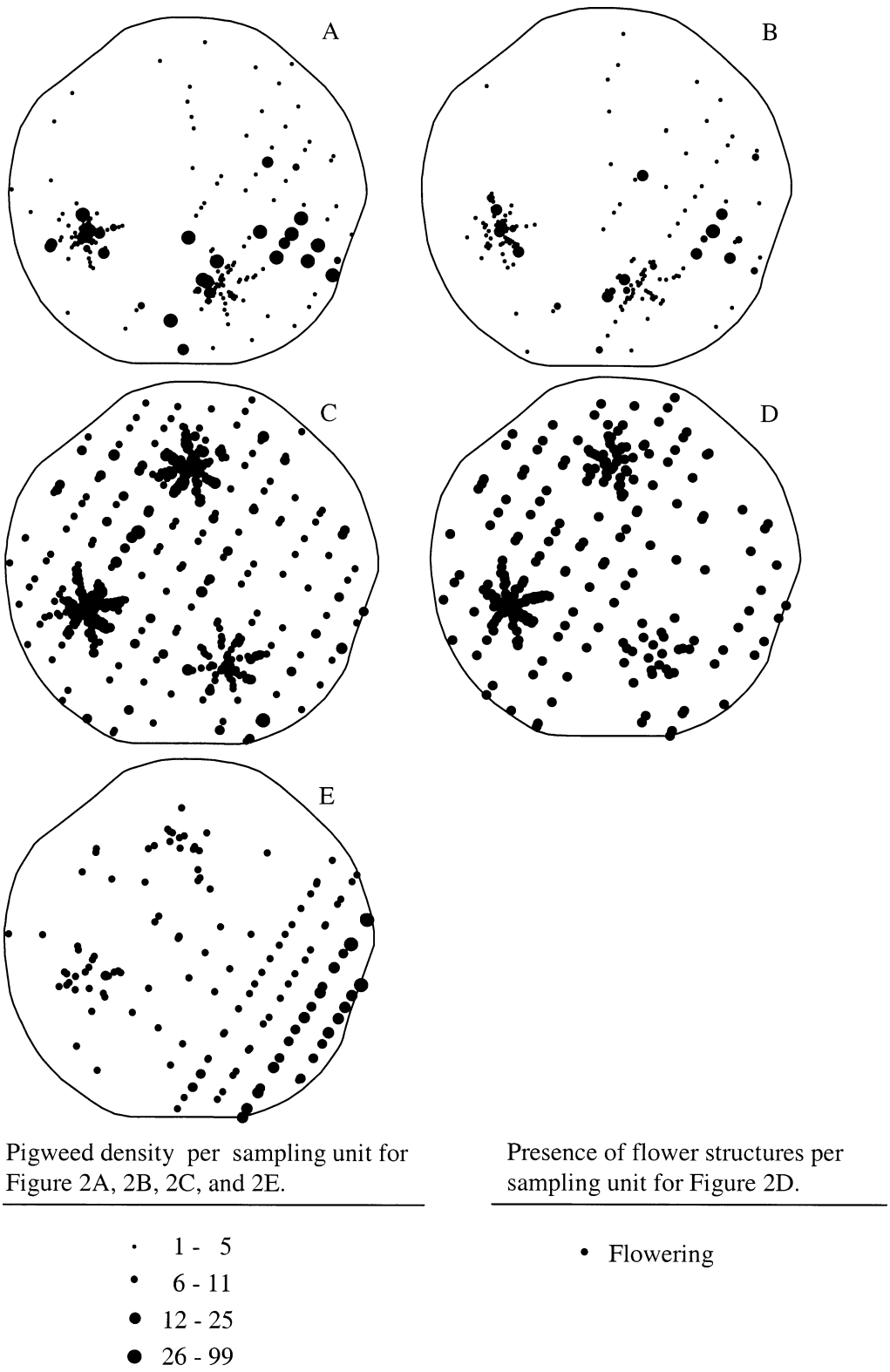

FIGURE 2. Pigweed plant (*Amaranthus*) density per sampling unit at each sampling site in Field 1 during 1997 at the (A) first, (B) second, and (C) third sampling times, (D) the presence of flower structures at the third sampling time in 1997, and (E) pigweed density the following year, 1998, at the first sampling time.

at the second sampling time and in Field 2 during 1998 at the first sampling time. The longest detected range was 363 m at 120° from the crop row (direction of the northwest prevailing winds) for pigweed plants in Field 1 at the second sampling time during 1998, but only 18% of the variation was explained by spatial dependence.

Spatial dependence for field sandbur was detected in both fields. Field sandbur was the only species in which spatial

TABLE 6. Variogram parameters of the range and nugget for weed species when spatial dependence was detected by field, year, and sampling time during 1997 and 1998 for six examined directions.[a]

Sampling time[c]	Species	Variogram parameters																			
		Field 1												Field 2							
		1997							1998					1998							
		Nugget	Range						Nugget	Range				Nugget	Range						
			Degrees[b]							Degrees					Degrees						
			0	30	60	90	120	150		0	30	60	90	120	150		0	30	60	90	120	150
1	*Amaranthus* species	—[d]	—	—	—	—	—	—	—	—	—	—	—	—	—	0.68	80	140	116	70	57	59
2	*Amaranthus* species	0.82	94	75	80	118	363	190	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1	CCHPA	0.51	98	21	14	13	16	31	0.28	30	10	6	5	6	11	0.55	61	26	18	18	23	47
1	CHEAL[e]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.43	43	34	25	22	25	33
1	*Solanum* species	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.69	55	104	60	38	33	36

[a] Variogram parameter of the sill is equal to one for each sample.
[b] Degrees clockwise from the row direction.
[c] Sampling time 1: before postemergence herbicide treatment at V2 corn; 2: after postemergence herbicide treatment at V4 corn.
[d] Dashes (—) indicate spatial dependence was not detected.
[e] Data only from sampling units on the northwest section of Field 2.

dependence was detected in the same field during both years (Table 4 and Figure 3). In Field 1 during 1997, field sandbur population had a nugget of 0.51 (Figure 3A) and ranges of 13 to 98 m for the investigated directions, whereas in 1998 the nugget decreased to 0.28 (Figure 3B) with ranges of 5 to 30 m for the investigated directions (Table 6). Between years and along the direction of the crop row, observed field sandbur densities were correlated to 98 m during 1997 but only correlated to 30 m during 1998 in Field 1 (Figure 3). A correlation coefficient of zero occurred for the sample of field sandbur when all sample units were field sandbur-free for a particular lag distance (Figure 3D).

For field sandbur in Field 2 during 1998, the nugget was 0.55 whereas the ranges were 18 to 61 m depending on direction (Table 6). For these three field sandbur samples, spatial dependence was detected at greater distances in the direction of the crop rows (30 to 98 m) than the other five directions (5 to 47 m), suggesting that field sandbur dispersal might occur more easily down the crop rows than across them. Greater ranges in the direction of the crop rows might be because of crop management, water, and wind (Howard et al. 1991; Johnson et al. 1996; Nordbo et al. 1994). Similarly, weed densities were more similar in the direction of the crop row in a study conducted by Johnson et al. (1996). Future sampling plans to create a reliable interpolated distribution map of weed densities in eastern Colorado fields, if and when sampling at the scale of spatial dependence is possible, should include observations at shorter separation distances for directions from the crop row than within the crop row.

Spatial dependence was not detected for common lambsquarters when all sampling units were evaluated (data not shown). Common lambsquarters density was correlated to 43 m in the direction of the crop rows in Field 2 during 1998 when only the sample units from the northwest half of the field were evaluated (Table 6 and Figure 4A). Detecting spatial dependence only from the sample units from the northwest half might be because of differences in crop rotations. In 1993, the northwest half of Field 2 was planted with sugar beet, whereas the southeast half was planted with pinto bean. The effect of crop rotation on weed infestation was investigated by Dotzenko et al. (1969), and they indicated that sugar beet grown after beans (*Phaseolus vulgaris* L.) in Colorado was always more weed-free than sugar beet grown after sugar beet, corn, or barley (*Hordeum vulgare* L.). Along with the difference in rotation, herbicide selectivity might have promoted the infestation of common lambsquarters in the northwest area when planted with sugar beet during 1993. Common lambsquarters control might not be as complete when the field is planted with sugar beet as when planted with a crop such as pinto bean because herbicide selectivity is often lower for weeds that occur within the same plant family as the crop (sugar beet and common lambsquarters are in the Chenopodiaceae family) (Dotzenko et al. 1969). As a result, future sampling plans should include observations at shorter separation distances when a field has been previously planted with certain crops.

Spatial dependence was detected for nightshade plants in Field 2 during 1998 before a postemergence herbicide was applied. The nugget was 0.69 and ranges for the six directions were 55 to 104 m (Table 6). Even though nightshade plants were detected in most of the sampling units (only

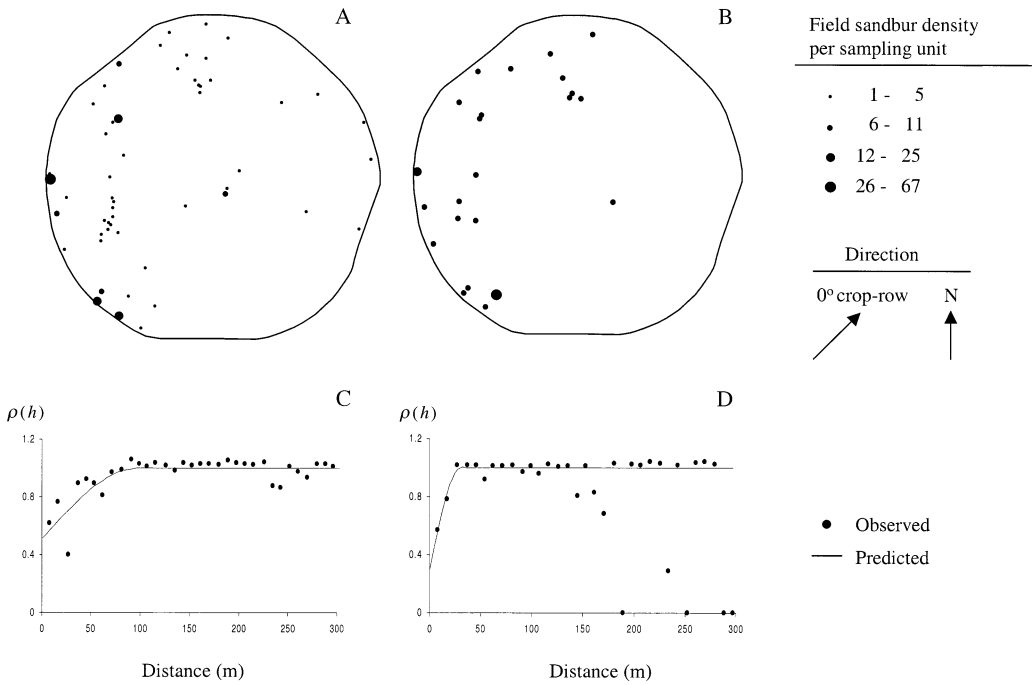

FIGURE 3. Field sandbur [*Cenchrus longispinus* (Hack.) Fern] plant density per sampling unit at each sampling site in Field 1 during (A) 1997 and (B) 1998, and (C and D) the transformed correlation values, $\rho(h)$, plotted against distance in the direction of the crop row (0°). Parameter values for the transformed correlation values are shown in Table 6.

17% were nightshade-free) (Table 5), 31% of the sample variation was explained by spatial dependence to 55 m in the direction of the crop rows (Figure 4).

Spatial dependence was not detected for many weed species and species complexes. The correlograms for the remaining samples often exhibited a pure nugget effect where there was no correlation between sampling units at any distance, and none of the variation in density was caused by spatial dependence. This suggests that the spatial distribution of these species is random at sampling distances (Wal-

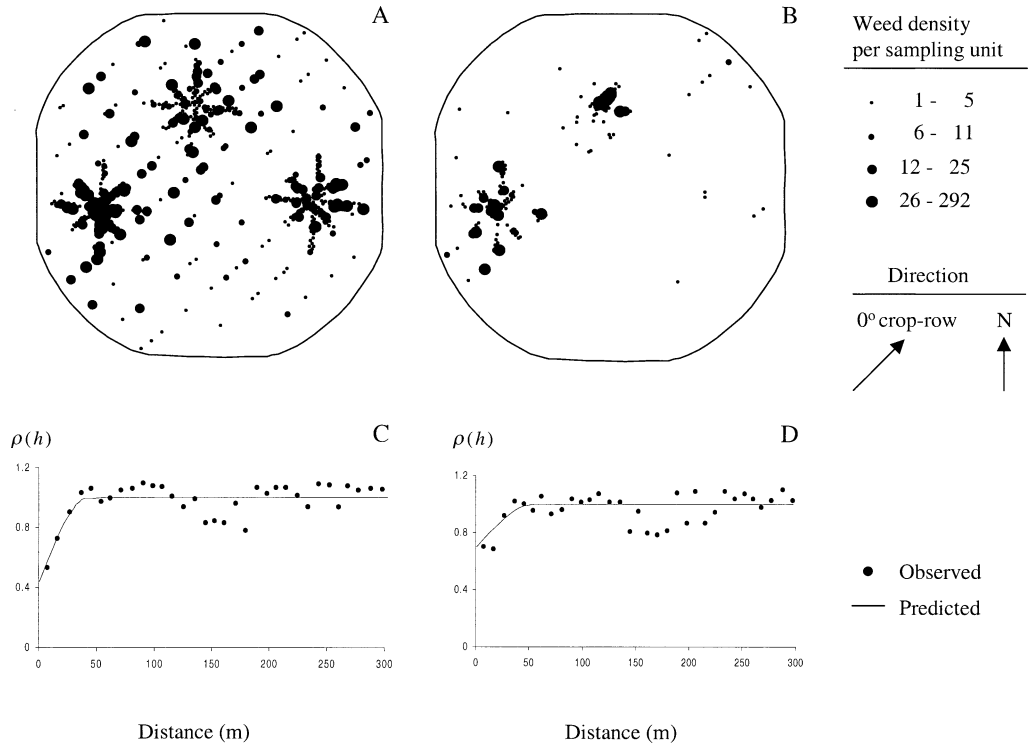

FIGURE 4. (A) Common lambsquarters (*Chenopodium album* L.) and (B) nightshade (*Solanum*) plant density per sampling unit at each sampling site in 1998 and (C and D) the transformed correlation values, $\rho(h)$, plotted against distance in the direction of the crop row (0°) for Field 2 in 1998 before a postemergence herbicide application. Parameter values for the transformed correlation values are shown in Table 6.

lace and Hawkins 1994) used in our study, although spatial dependence could occur at much smaller separation distances.

The lack of spatial dependence or the presence of large nugget effects may have been caused by inadequate sampling unit size and placement or human measurement error (sampling error) (Isaaks and Srivastava 1989; Liebhold et al. 1993; Rossi et al. 1992; Weisz et al. 1995). In particular, processes of seed dispersal, germination, and mortality may operate below the observed separation distances between sample sites in this study. In order to assess adequately whether spatial dependence exists for weed species, more sampling units need to be placed at shorter separation distances (possibly less than 7.62 m throughout the entire field in multiple directions). Also, Weisz et al. (1995) determined that sampling unit size might explain the frequency of finding pure nugget effects. When the Colorado potato beetle (Coleoptera: Chrysomelidae) was resampled with a larger sampling unit, the experimental error decreased, whereas precision increased, and spatial dependence was detected (Weisz et al. 1995).

Total weed seedling or mature plant sampling programs for map generation should not be developed for irrigated corn fields in eastern Colorado with only the information gathered in this study. To create an accurate distribution map of the total weed infestation, weed populations must exhibit spatial dependence. However, for only 7 of the 93 samples could an interpolated map be created. Because of the minimal detection of spatial correlation for weed seedling distributions in eastern Colorado corn fields, interpolated density maps should not be created from a 7.62-m grid for weed seedling infestations because knowing a weed density at one field location would not provide any information about the weed density at an unsampled location with the employed sampling method. In addition, for the seven samples where spatial dependence was detected, weed densities were correlated at short distances well below 363 m for the six directions that were observed, indicating that numerous weed observations would be necessary to create an accurate map for only a few species.

Sources of Materials

[1] OmniSTAR 7000 differential global positioning system, OmniSTAR Inc., 8200 Westglen, Houston, TX 77063.

[2] SAGE95 geostatistical software, Isaaks & Co., 205 E. 3rd Avenue, Suite 300, San Mateo, CA 94401.

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